

Turbidity and suspended solids levels and loads in a sediment enriched stream: implications for impacted lotic and lentic ecosystems*

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Abstract

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The implementation of an automated stream monitoring unit that features four probe-based turbidity (T_n) measurements per hour and the capability to collect frequent (*e.g.*, hourly) samples for total suspended solids (TSS) analyses during runoff events to assess the dynamics of T_n , TSS and corresponding loads in sediment-rich Onondaga Creek, NY, was documented. Major increases in both T_n (maximum of 3,500 NTU) and TSS (maximum of 1630 mg/L) were reported for the stream during runoff events. Relationships between T_n , TSS and stream flow (Q) were developed and applied to support estimates of TSS loading (TSS_L). T_n was demonstrated to be a better predictor of TSS than Q , supporting the use of the frequent field T_n measurements to estimate TSS_L . During the year of intensive monitoring, 65% of the TSS_L was delivered during the six largest runoff events that represented 18% of the annual flow. The high T_n levels and extensive in-stream deposition have negatively impacted the stream's biota and the esthetics of a downstream harbor. Onondaga Creek is reported to be the dominant allochthonous source of inorganic particulate material to downstream Onondaga Lake. These sediment inputs have important implications for the lake, within the context of two on-going rehabilitation programs aimed at contaminated lake sediments and the effects of extreme cultural eutrophication, by contributing substantially to sedimentation and turbidity. A satellite image documented the occurrence of a conspicuous turbidity plume that emanated from Onondaga Creek following a minor runoff event, suggesting such an effect is common and that related impacts are not spatially uniform.

Key Words: turbidity, total suspended solids, loads, runoff events, stream impacts, lake impacts, satellite imagery

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Inanimate terrigenous sediment plays important roles in the ecology and water quality of both lotic and lentic ecosystems by presenting reactive surfaces for critical constituents, (O'Connor 1988, Tessier 1992, James and Barko 1997) influencing metabolic activity and composition of biological communities of water columns (Lythgoe 1979, Hart 1988, Newcombe 2003) and bottom sediments (Henley *et al.* 2000), contributing to net sedimentation and deposits subject to subsequent resuspension (Lick *et al.* 1995), and attenuating light through the process of light scattering (Kirk 1985, Effler *et al.* 2002b, 2006b). These various effects depend on different physical attributes of the particle assemblage, such as surface area in the case of sorption/desorption processes (Tessier 1992), combined size and density features for deposition and resuspension (Lick *et al.* 1995), and projected area in the case of light scattering (Beardsley *et al.* 1970, Treweek and Morgan 1980).

Assessments of potential effects of sediment in aquatic ecosystems have most often been based on the gravimetric measurement of the concentration of total suspended solids (TSS in mg/L). The next most commonly used metric of particle impacts is turbidity (T_n in NTU). Turbidity, which quantifies light scattered by particles from a beam centered on 90° (Kirk 1994), is the most widely measured surrogate metric of the scattering coefficient (DiToro 1978, Kirk 1981, Effler 1988). Relationships between TSS and T_n are not always strong and generally vary among systems (Davies-Colley and Smith 2001) because of the fundamental differences in the particle size and composition dependences of mass concentration and light scattering.

Inanimate particle concentrations vary temporally and spatially in aquatic ecosystems, patterns that have both water quality and ecologic implications. Temporal patterns in lotic systems are of interest within the context of impacts on the stream environment, as well as downstream lentic systems. Effects of runoff events are of particular concern because of widely observed increases in particle concentration and related metrics during these intervals (Effler *et al.* 1992, Longabucco and Rafferty 1998, Davies-Colley and Smith 2001, O'Donnell and Effler 2006). A large portion of the sediment load carried by many streams annually occurs in relatively brief intervals of high flow (Richards and Holloway 1987, Longabucco and Rafferty 1998).

Monitoring both TSS and T_n in streams has at least two advantages. First, this combination provides a more robust representation of particle impacts. Suspended solids concentrations reflect potential effects on mass deposition and resuspension, while T_n represents optical impacts associated with light scattering (*e.g.*, light penetration, clarity, reflectance from the water surface; Kirk 1994) that affect esthetics and the public perception of water quality (Effler 1988). Quantification of loads is desired in assessments of

potential impacts as these assessments are critical inputs for mathematical models of water quality within streams (Lick *et al.* 1995) and for downstream lakes and reservoirs (Chapra 1997). Total suspended solids loading (TSS_L in kg/d) is widely estimated to address particle impacts within streams and aquatic systems downstream. Recently the advantage of developing turbidity (*e.g.*, light-scattering) "loads" instead of TSS_L for streams to support mathematical modeling of turbidity in downstream lakes and reservoirs was described (Gelda and Effler 2006). A "quasi-mass balance" modeling approach for turbidity (as the state variable) is supported by the additive character of components and sources of light scattering (Davies-Colley *et al.* 1993).

The second advantage of monitoring both TSS and T_n is to support improved TSS_L estimates with more frequent T_n measurements. Historically, estimates of TSS_L were supported for gauged streams by frequent flow measurements (Q in m^3/s) from continuous monitoring gauges and comparatively few TSS observations, which were limited by practical sampling and laboratory constraints. System-specific empirical relationships between TSS and Q were often developed and applied to support development of estimates of TSS_L in such cases (Campbell and Bauder 1940, Miller 1951, Manczak and Floreczyk 1971). Improved estimates of TSS_L were developed through increased sampling and TSS analyses that targeted runoff events (Yaksich and Verhoff 1983, Richards and Holloway 1987). This approach has been facilitated through use of automated sampling equipment (Longabucco and Rafferty 1998); nevertheless, laboratory constraints of practical analytical efforts limit this approach. The use of T_n as a surrogate of TSS offers potential for more accurate TSS estimates where frequent *in situ* T_n observations are available from deployed instrumentation (Walling 1977, Christensen *et al.* 2002). This instrumentation can support resolution of temporal patterns over time scales that cannot reasonably be addressed by programs based on sampling and analyses for TSS. This approach relies on the premise that the TSS- T_n relationship is stronger than the TSS- Q relationship, a condition believed to prevail in many lotic systems (Christensen *et al.* 2002).

This paper documents the implementation of an automated monitoring unit to assess the dynamics of T_n , TSS and corresponding loads for a stream enriched with terrigenous sediment. As part of the analysis, relationships between T_n , TSS and Q were developed and evaluated. The dependences of loading estimates for T_n and TSS on the frequency of measurements were evaluated. Finally, the stream's sediment loading was considered within the context of impacts on the stream and a downstream lake, and implications for rehabilitation initiatives for the lake.

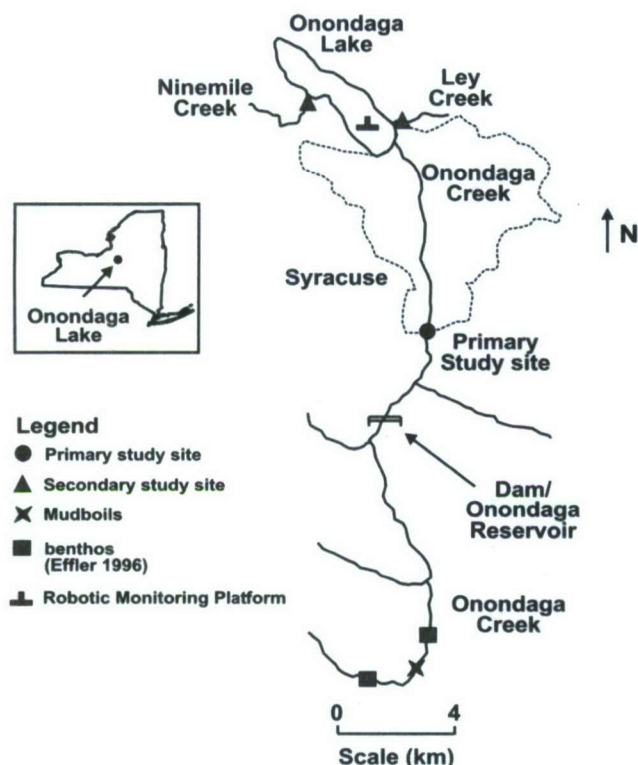


Figure 1. Onondaga Creek, Onondaga Lake and the city of Syracuse (dotted outline), with position within New York. Locations of primary and secondary study sites, flood control dam (Onondaga Reservoir), mudboils, and macrobenthos monitoring sites included.

Study site

The headwaters of the study stream, Onondaga Creek, originate 44 km south of the city of Syracuse, NY (Fig. 1). Onondaga Creek drains a 298 km² watershed of mixed land use (~80% forest, rural and agriculture and ~20% urban) and flows north through the Tully Valley where it enters first a harbor and subsequently Onondaga Lake in Syracuse (Fig. 1). At the primary study site, Dorwin Avenue, located upstream of the city (Fig. 1), the stream has been gauged continuously since 1951 (rating of this gauge is good) by the United States Geological Survey (USGS, site no. 04239000). The mean and median daily flows at Dorwin Avenue for the period of record are 3.59 and 2.27 m³/s, with a range of 0.16–48.42 m³/s. A flood control dam and reservoir located 6.4 km upstream of Dorwin Avenue, within the Onondaga Nation Reservation, regulates the peak flow that reaches Syracuse. This structure influences the stream flow (*Q*) pattern only for larger runoff events (*i.e.*, when *Q* exceeds ~20 m³/s). Accordingly, a portion of the high flow is diverted into the reservoir during these intervals and then released back into the stream during recession. Annually, Onondaga Creek contributes approximately 30% of the hydrological input to Onondaga

Lake (Effler 1996). The other major natural tributaries of the lake, Ninemile Creek and Ley Creek, contribute about 30% and 8%, respectively; effluent from a domestic waste water treatment facility represents ~20%.

Onondaga Creek receives particle inputs from hydrogeologic point sources termed “mudboils” (sediment brought to the surface by artesian discharge; Shlits 1978) located 33 km upstream of Onondaga Lake (Fig. 1). Mudboils were first reported in this area in the late 1880s (Kappel and McPherson 1998). Sediment from the mudboils is composed mostly of clay minerals, the primary component carried by the stream and input into Onondaga Lake (Effler *et al.* 1992). There has been substantial debate (Effler 1996) concerning the extent to which the sediment load from these sources is associated with a proximate solution mining facility that was operated by a soda ash/chlor-alkali industry (located on the western shore of Onondaga Lake) from 1884 to 1986. Sediment loading from the mudboils was reduced ~90% in the mid-1990s through an array of remedial measures (Kappel and McPherson 1998). Substantial sediment deposits exist along the stream banks and bottom downstream of the mudboils, but upstream of the study site (Effler *et al.* 1992), presumably composed of sediment from the mudboils.

Methods

Automated stream monitoring unit and supporting measurements

Monitoring of TSS and *T_n* in Onondaga Creek was conducted at Dorwin Avenue from October 2003 through September 2004 (USGS water year 2004) using an automated monitoring unit (Fig. 2a). The unit was housed within a USGS gauging hut, and its monitoring functions (frequency and water sampling) were controlled remotely by commands delivered by a base station computer via phone (Fig. 2b). Collected data were transmitted back to the base station in near-real-time (NRT). Contemporary monitoring data are posted at a public domain web site (www.ourlake.org) in NRT, providing access for a wide range of stakeholders (Fig. 2b). The automated monitoring unit received stream water continuously during the study via a submersible pump located at mid-channel. Water was pumped through a 57-L vessel (flow velocity of approximately 30 cm/s was maintained), where monitoring probes and a sampling line were positioned, and then returned to the creek (Fig. 2a). Automated *T_n* measurements and water chemistry samples were collected from the sampling vessel, as opposed to from the creek directly, to prevent instrumentation damage or loss.

Water samples were collected according to remote commands made through the monitoring unit computer to an automated refrigerated sampler (ISCO® 6712). Samples were collected at least once every two weeks during baseflow conditions.

The frequency increased substantially during nine runoff events, usually 6-12 d⁻¹. Adjustments in sampling frequency were made occasionally during storms through remote commands. A total of 167 samples were collected by the automated monitoring unit during this study and analyzed in the laboratory (APHA 1992; Table 1) for T_n, TSS, and fixed (non-volatile) suspended solids (FSS). Automated measurements of T_n were made with datasondes configured with turbidity probes in the 57-L vessel (Table 1). Stream turbidity was well represented by the automated monitoring unit as verified by comparison to *in situ* observations collected with the same instrumentation. Measurements were made every 15 min during the intervals of successful operation of the monitoring unit. However, interruptions were encountered, associated mostly with meteorologic extremes. For example, interruptions from clogging of the in-stream pump occurred occasionally during high runoff events. At least one turbidity measurement was made for 75% of the days; 75% coverage (≥ 72 measurements out of 96) within a day was achieved for approximately 70% of the study days. A total of 23,905 turbidity measurements were collected by the automated monitoring unit for the study period.

Throughout the course of the investigation, systematic differences in T_n were observed between the Hydrolab and YSI turbidity probes (based on paired *in situ* deployments). Because of these differences, both sets of field turbidity measurements were adjusted to laboratory values based on regression analyses (Table 2) using paired field (probe) and laboratory measurements. The values of T_n reported here and used in calculations based on this metric correspond to those measured in the laboratory with a Hach model 2100AN turbidimeter. The relationships for both field probes (different manufacturers) were strong ($r^2 > 0.98$), though they provided observations that were systematically higher than

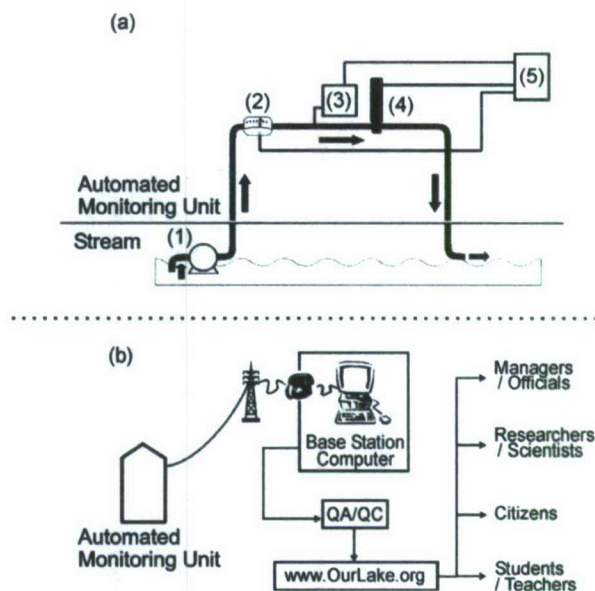


Figure 2.—Automated stream monitoring unit: (a) identification of components (1) in-stream pump, (2) flow meter, (3) ISCO® 6712 autosampler, (4) datasonde fitted with turbidity probe, and (5) field computer, and (b) schematic of pathways for data transfer and dissemination to stakeholders.

those obtained with the laboratory turbidimeter (Table 2). The modest deviation from linearity for one of the probes was associated with very high levels of turbidity.

In addition, a fixed-frequency (bi-weekly) manual TSS monitoring program was conducted for Onondaga Creek (primary study site), Ninemile Creek, and Ley Creek from 2001 to 2005. Samples were collected near USGS gauges and adjoining the mouths (secondary study sites; Fig. 1) of Ninemile

Table 1.—Instrument specifications.

Instrument	Model	Parameter	Detection Range	Accuracy	Resolution
Field Instrumentation					
YSI 6600	-	T	-5-45°C	±0.15°C	0.01°C
Multiprobe	-	*T _n	0-1000 NTU	±5% or 2 NTU	0.1 NTU
Hydrolab	-	T	-5-50°C	0.1°C	0.01°C
Datasonde 4	-	*T _n	0-3000 NTU	±1-5% (range)	0.1-1 NTU (range)
ISCO® automated sampler	6712	-	-	-	-
Lab Instrumentation					
Turbidimeter	HACH 2100 AN	T _n	0-10,000 NTU	±2%	0.001 NTU

* model No. 6136

Hydrolab Self-cleaning T_n probe

Table 2.—Relationships to adjust field probe measurements of T_n to laboratory values.

Deployment Interval	Field Probe	Correction Equation	N	r ²
Oct. 1, 2003 to April 6, 2004	YSI 6136	Lab $T_n = 0.06 + 0.79 \cdot (\text{Probe } T_n)$	68	0.98
April 22, 2004 to Sept. 30, 2004	HYDROLAB Self-cleaning T_n	Lab $T_n = -1.34 + 0.64 \cdot (\text{Probe } T_n) + 0.0002 \cdot (\text{Probe } T_n)^2$	176	0.99

Creek (USGS site No. 04240300) and Ley Creek (USGS site No. 04240120). This fixed-frequency program served to support estimates of the contributions of these streams to overall tributary TSS loading to Onondaga Lake.

Relationships and loading estimates

Relationships between TSS and T_n , TSS and Q, and T_n and Q, at the Dorwin Avenue site during the study period were evaluated based on paired instantaneous measurements, through linear least squares regression, in the commonly adopted (Davies-Colley and Smith 2001) log-transformed format. Two TSS-Q relationships were quantified for the Dorwin Avenue site in 2004: one utilizing paired, instantaneous values of TSS and Q, and the second using biweekly TSS values paired with corresponding daily averaged Q. Additionally, TSS-Q relationships were developed for the Dorwin Avenue site over the 1988-1990 interval (Effler 1996) and for the Dorwin Avenue site and two additional streams (Ninemile Creek and Ley Creek) over the 2001-2005 interval. These later analyses were based on daily average flow instead, because these are the most frequent flow values reported for Ninemile Creek (gauge performance rated as fair). The magnitudes of runoff events for Onondaga Creek during the study period are represented by calculated return frequencies, based on an analysis of daily average flow values from the Dorwin Avenue gauge for the period of record. Accordingly, a return frequency of 2/y for an event indicates the daily average flow for that event is exceeded, on average, on two days (twice) per year.

Loading estimates for T_n ($T_{n/L}$; NTU·m³/d) for Onondaga Creek for water year 2004 were determined as the summation of the products of T_n and Q for each i interval and the time interval (Δt_i)

$$T_{n/L} = \sum_{i=1}^n T_{n/i} \cdot Q_i \cdot \Delta t_i \quad (1)$$

where n equals the numbers of paired observations. The value of Δt was 30 min, to be consistent with the available of instantaneous Q observations. Values of T_n for intervals without measurements from the automated monitoring unit were specified from Q_i values according to the determined T_n -Q relationship. The values of TSS_L (mt/d) for water year

2004 were based on $T_{n/i}$ observations, when the automated monitoring unit functioned, based on the determined TSS- T_n relationship. When $T_{n/i}$ observations were not available, values of TSS were specified directly from the TSS-Q relationship. This approach for the intervals of missing T_n observations avoided the introduction of two sources of uncertainty in TSS_L estimates that would accompany serial application of the T_n -Q and TSS- T_n relationships.

To investigate the dependence of loading estimates on monitoring frequency, the full T_n dataset for water year 2004 was manipulated (observations deleted) to represent less frequent monitoring schedules for two runoff events (No. 31 and 33, subsequently) and for the May-September interval. The time intervals between measurements were extended to 1, 2, 4, 8, 12, and 24 h for the runoff events, and to 1, 2, 4, 7, and 14 d over the May-September interval. Linear interpolation was used to estimate T_n between the specified time intervals and loads were calculated according to the protocols described above. The effects of the different monitoring intervals on calculated loads were represented on a percent difference basis, relative to the 30 min interval data.

Evaluation of Onondaga Creek's contribution to overall tributary TSS loading to Onondaga Lake was based on the bi-weekly monitoring program results for the three largest tributaries for five consecutive water years, 2001-2005. Loads were calculated as the summation of the products of daily average flow and TSS concentration, according to each tributary's flow and TSS-Q relationship. Values of TSS_L for Dorwin Avenue were generally representative of conditions at the mouth of Onondaga Creek (Effler 1996).

Remote sensing characterization of sediment in downstream lake

Remote sensing characterizations of turbidity patterns in the upper layers of Onondaga Lake on September 29, 2002 utilized an Advanced Landset Imager (ALI) image. This image was processed to assess the spatial patterns of the beam attenuation coefficient at 550 nm (c_{550}) throughout Onondaga Lake. Like T_n , c_{550} is a surrogate metric of the light scattering coefficient; these measures are generally highly correlated (Effler *et al.* 2006b; $T_n = 2.33 \cdot c$, $r = 0.93$). ALI

is a multi-spectral imager on board NASA's EO-1 satellite. It has four wide spectral bands in the visible domain with spatial resolution of 30 m for each band.

The ALI data were converted to remote sensing reflectance (R_{rs}) values, after correcting for atmosphere effects (Lee *et al.* 2005). Fundamentally, R_{rs} is a function of two inherent optical properties of water, the absorption (a) and backscattering (b_b) coefficients. These properties are controlled by various particulate constituents (*e.g.*, inorganic particles, detritus, and phytoplankton) as well as dissolved organic material. Estimates of c_{550} from R_{rs} were based on two algorithms applied in series. The first derives values of a and b_b from R_{rs} observations (Lee *et al.* 2002). The second estimates c_{550} from a and b_b (Lee *et al.* 2006).

Results and discussion

Dynamics of Q , T_n and TSS

Water year 2004 had the third highest mean daily flow (5.53 m^3/s) over the 54-year record. Thirty-eight runoff events were identified for this study period (Fig. 3a), based on an event criterion of an increase of 1.4 m^3/s in less than two days. Flow was particularly high compared to the long-term average in late fall through early winter and late summer for this water year (Fig. 3a). The six largest runoff events, quantified by peak discharge (No. 10, 13, 17, 22, 33 and 36; Fig. 3a), accounted for 18% of the total flow for the water year.

Major variations in T_n occurred over the study period (Fig. 3b, note the logarithmic scale adopted to represent the pattern of daily average values). Increases of T_n occurred repeatedly during runoff events. The magnitude of increases generally tracked those of the runoff events; for example, the peak flows of the events (Q_p) explained 67% of the peak T_n values, according to linear least squares regression. The highest daily average T_n value exceeded 1500 NTU (August 31), while values <10 NTU were observed during certain low flow intervals (Fig. 3b). Most of the missing T_n observations occurred in winter and early spring, associated with the most challenging conditions (*e.g.*, cold, ice, high Q) for the automated monitoring system.

Turbidity levels also demonstrated great sensitivity to Q from the onset through the progression of individual runoff events, as illustrated for both a minor (Fig. 4a; 269/y) and a major (Fig. 4b; 9/y) runoff event. Event No. 31 (Fig. 4a) had a Q_p of 7.14 m^3/s , that represented an increase in Q of 5.27 m^3/s within 17 h. Turbidity increased strongly on the rising limb to a value of about 240 NTU, followed by a short-term decrease and re-increase to a peak of more than 330 NTU 2 h after Q_p (Fig. 4a). The increase in T_n from antecedent conditions (14 NTU) to peak T_n (337 NTU) was more than 20-fold. The less frequent TSS observations demonstrated a

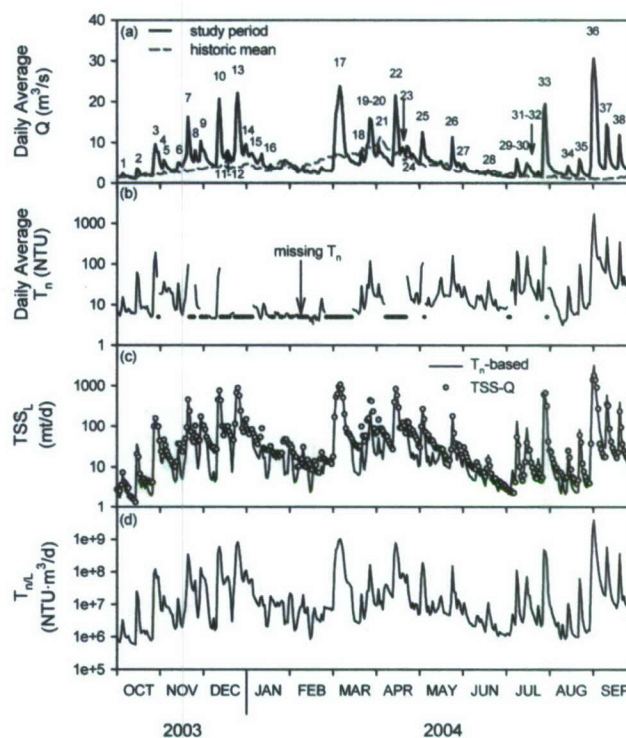


Figure 3.—Time series of primary study site on Onondaga Creek for water year 2004: (a) flow (Q), with runoff events labeled and long-term average for comparison, (b) daily average turbidity (T_n) with data intervals identified, (c) comparison of daily total suspended sediment loading (TSS_L) based on T_n monitoring versus TSS- Q relationship, and (d) daily turbidity load (T_{nL}).

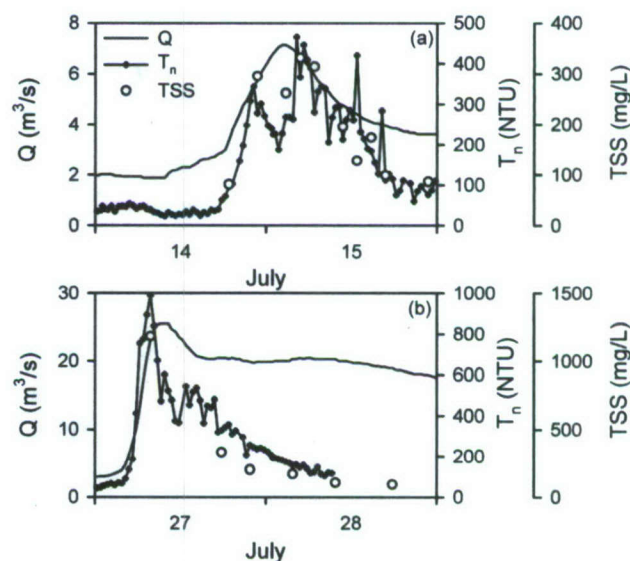


Figure 4.—Time series of Q , T_n , and TSS at primary study site for selected runoff events: (a) event No. 31, July 14-15, 2004, and (b) event No. 33, July 28-29, 2004.

similar response, increasing about 10-fold from 35.4 mg/L to 330 mg/L at the peak flow. Both T_n and TSS decreased rapidly on the falling limb of the hydrograph. The shape of the hydrograph for event No. 33 was different than event No. 31, as uniformly high flows persisted for more than a day after the peak flow (Fig. 4a and b). This shape was recurring for the largest events of the study and reflected the effects of the operation of the upstream flood control reservoir (>20 m³/s). The plateau of relatively high flow following the peak represented inputs of stream water that had been diverted to the reservoir earlier in the event. The increases in T_n were even more dramatic for this larger runoff event compared to the smaller event No. 31 (Fig. 4a and b). Turbidity increased to a peak value of 820 NTU, 3 h prior to the flow peak. The more infrequent TSS observations suggested a similar temporal pattern. Approximately 50-fold increases in both T_n and TSS were observed from antecedent base flow conditions to the runoff peak values. However, strong divergence in the patterns of these metrics of particle content from the hydrograph was manifested following the peak flow. Both T_n and TSS decreased rapidly over the interval of the flow plateau maintained from the reservoir releases. This inconsistency in the patterns of T_n (and TSS) and Q was recurring for all events in which the upstream reservoir influenced the hydrograph.

The contrasting features of the paired temporal patterns of T_n and Q following the peak flow of the largest runoff events (e.g., Fig. 4b) provided insights concerning the function of the upstream reservoir and the origins of the sediment reaching the study site. The relatively low and progressively decreasing T_n and TSS levels following the peak flow indicated the operation of an upstream loss process for suspended sediment during this interval, presumably attributable to sediment deposition within the flood control reservoir. Accordingly, a portion of the sediment load carried in the stream above the reservoir during large runoff events was intercepted by, and lost within, this flood control structure. These features further indicated that most of the sediment load that reaches the study site was received from areas upstream of the reservoir and downstream of the mudboils (Fig. 1). This observation was consistent with the findings of an earlier study (Effler *et al.* 1992) that focused on the origins of suspended sediment in this stream. The in-stream sediment deposits were located well upstream of the reservoir (Fig. 1).

Interrelationships

Suspended solids in Onondaga Creek were dominated by inorganic material, with average and median FSS/TSS ratio values of 0.89. This fraction was generally uniform across the entire range of Q . These observations were consistent with the findings of earlier studies that reported clay minerals were the dominant form of suspended particles in this stream (Yin and Johnson 1984, Effler *et al.* 1992). The above ratio

value may actually understate the inorganic fraction because clay minerals can lose structural water at the temperature employed in the volatile suspended solids analysis (Mook and Hoskins 1982).

A strong ($r^2 = 0.91$) highly significant ($p < 0.0001$) relationship existed between TSS and T_n over the study period (Fig. 5a). Sources of scatter include analytical imprecision and variations in particle size distribution. The full data set was stratified into two seasons (October-March and April-September) and three hydrograph stages (base flow, rising limb, and falling limb). Separate TSS- T_n relationships were generated for each stratum using linear least-squares procedures as described previously. No statistically significant differences were observed for the TSS- T_n relationships (Homogeneity-of-slopes model; Statistica 6.1, StatSoft, Inc. 2003) for these time segments ($p = 0.262$) or between different hydrograph stages ($p = 0.162$), indicating that T_n is a stable surrogate of TSS. This demonstrated success of T_n as a surrogate metric of TSS supported the application of frequent T_n measurements to support testing of watershed models in simulating TSS dynamics.

A highly significant ($p < 0.0001$) positive relationship existed between TSS and Q over the study (Fig. 5b), though it was not as strong ($r^2 = 0.65$) as the TSS- T_n relationship (Fig. 5a). Some of the scatter in the TSS- Q relationship was attributable to the inclusion of observations for the largest runoff events following peak flow, when the functioning of the upstream reservoir caused lower TSS levels (e.g., Fig. 4b). However, no statistical difference ($p = 0.368$) was observed in the TSS- Q relationship for the rising and falling limbs of the hydrograph using a Homogeneity-of-slopes model (Statistica 6.1, StatSoft, Inc. 2003). The T_n data set from this study supported evaluations of the T_n - Q relationship at various time steps. Using the same portion of this data set that supported the development of the TSS- T_n relationship (Fig. 5a) allowed direct comparison with the performance of the TSS- Q relationship (Fig. 5b). The T_n - Q relationship ($p < 0.0001$; $r^2 = 0.65$) that results (Fig. 5c) was generally similar to that observed for the TSS- Q relationship, consistent with the character of the TSS- T_n relationship. Increasing the population of T_n measurements used from the collected data set in the analysis did not result in stronger T_n - Q relationships.

The TSS- Q relationship provided an appropriate format to evaluate differences associated with temporal coverage in monitoring, to identify systematic shifts in response to changes in drivers, and to compare loading potential for different streams. Differences in TSS- Q relationships were evaluated using a Homogeneity-of-slopes model (Statistica 6.1, StatSoft, Inc. 2003). The TSS loading potential was the highest (steepest slope) for Onondaga Creek when based on the complete (instantaneous) TSS and Q data set of water year 2004, compared to cases of bi-weekly (daily aver-

aged, fixed-frequency) monitoring for the same water year ($p=0.353$) and for the 2001-2005 ($p<0.0001$) period (Fig. 5d). The lower slopes obtained for the relationships based on less frequent fixed frequency monitoring (Fig. 5d) were consistent with under-representation of runoff events. The results from a bi-weekly monitoring program for TSS for this site on Onondaga Creek for the 1988-1990 interval (Effler 1996) represent the only known opportunity to identify a potential benefit from reductions in external loading achieved for the mudboils (Kappel and McPherson 1998). The relationship from this earlier period depicted a significantly ($p<0.0001$) lower loading potential compared to that based on the complete data set for water year 2004. However, it was not significantly different ($p>0.05$) from the contemporary relationships based on the same bi-weekly monitoring frequency. Thus, there is no compelling evidence that there has been a systematic decrease in the TSS loading potential of this stream in response to reductions in inputs from the mudboils. A potential explanation for these observations is that loading has remained dominated by stream bed and bank deposits (internal sources) formed from decades of mudboil inputs, and that the availability of this material (e.g., via resuspension processes) has yet to diminish.

The TSS-Q relationships for Ninemile Creek and Ley Creek were also positive (Fig. 5e) and significant ($p<0.0001$) for the 2001-2005 period (Table 3). The strongest relationship for the three tributaries ($r^2 = 0.399$) was observed for Onondaga Creek ($r^2 = 0.206$ and 0.166 , for Ninemile Creek and Ley Creek, respectively; Table 3). The steepest slope, or greatest loading potential, was observed for Onondaga Creek; significantly higher (Homogeneity-of-slopes model, Statistica 6.1; StatSoft, Inc. 2003) than for Ninemile Creek ($p=0.018$) and Ley Creek ($p<0.0001$).

Loading estimates

The time series of TSS_L estimates based on T_n measurements (when available) was compared to those derived strictly from the TSS-Q relationship (Fig. 3c); these were presented on a logarithmic scale to accommodate the wide range of calculated loads (~ 1 to 3200 mt/d). The estimates were necessarily equivalent during intervals that lacked T_n observations. Estimates based on the TSS-Q relationship were somewhat higher during low flow intervals and somewhat lower for falling limbs of certain large runoff events, but generally tracked those based on T_n measurements reasonably well. The loads based on T_n measurements were favored because the observations of this surrogate were much more frequent than TSS and because of the systematic limitations of the TSS-Q relationship for this stream on the falling limbs of major runoff events (Fig. 4b) associated with the operation of the upstream flood control reservoir. The limitations of the TSS-Q relationship during large runoff events could probably be corrected by development of a more complex

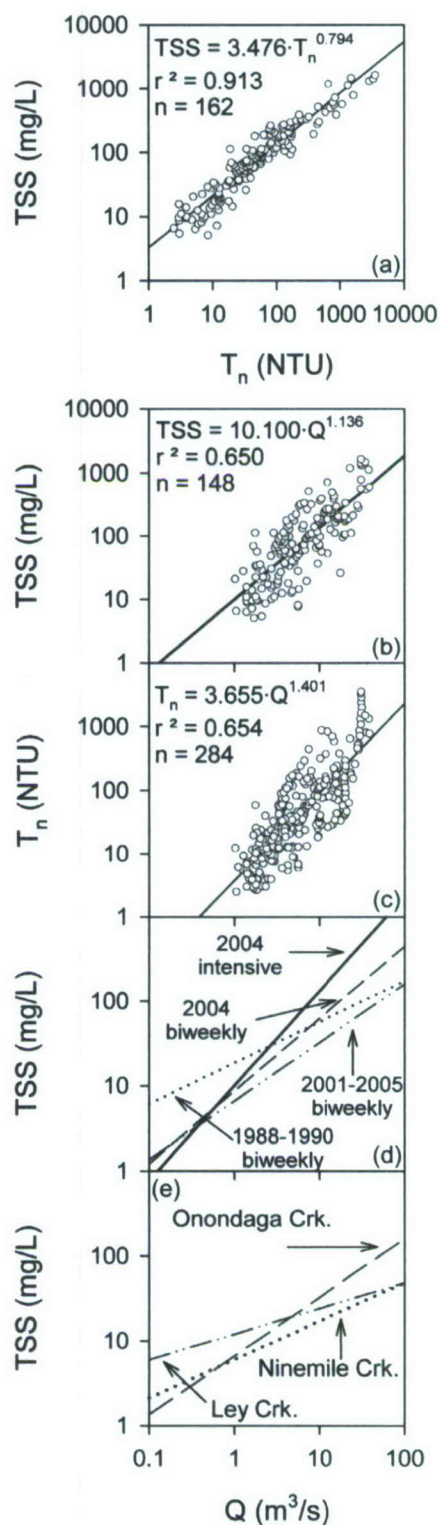


Figure 5.—Evaluation of relationships: (a) TSS- T_n at primary study site (instantaneous laboratory values), water year 2004, (b) TSS-Q at primary study site, water year 2004 (instantaneous values), (c) T_n -Q at primary study site, water year 2004 (instantaneous values), (d) TSS-Q at primary study site, for different data collection frequencies in water year 2004 and years of bi-weekly (daily averaged values) monitoring, and (e) TSS-Q for the primary and secondary study sites for bi-weekly monitoring for the 2001-2005 period (daily averaged values).

Turbidity and suspended solids levels and loads in a sediment enriched stream: implications for impacted lotic and lentic ecosystems

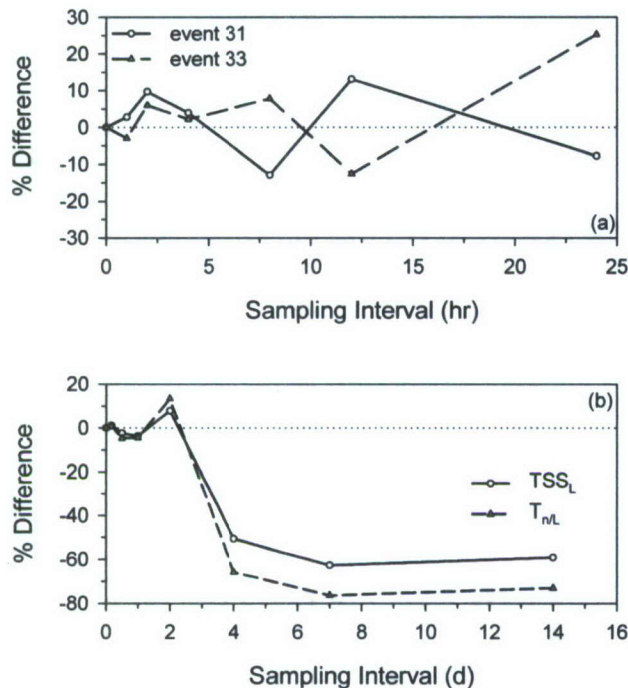


Figure 6.—Evaluation of dependence of loading estimates on the time interval of T_n measurements, relative to estimates from 30 min interval observations: (a) TSS_L for runoff event No. 31 and 33, and (b) TSS_L and T_{nL} for the May through September interval of 2004.

empirical model for the stream (*e.g.*, supported by additional monitoring) that stratifies large events according to the rising and falling limb (*e.g.*, “reservoir operations”) intervals. The annual estimates of TSS_L based on the TSS - Q relationship were higher (32,855 mt; average $TSS = 170$ mg/L, $n = 168$), in part because of the overprediction of load for the falling limbs of major runoff events, but were within 10% of that based on T_n monitoring (29,734 mt). The vast majority of the TSS_L was transported during runoff events; 85% of the load was delivered during the thirty-eight runoff events (Fig. 3a and 3c). Approximately 65% of the study TSS_L load was transported during the six largest events (No. 10, 13, 17, 22,

33 and 36), which corresponded to about 18% of the flow for the water year. A similar temporal pattern of T_n loads was obtained (Fig. 3d) that was related to the TSS_L pattern according to the TSS - T_n relationship (Fig. 5a).

Loading estimates were found to depend strongly on the frequency of T_n measurements (Fig. 6). Adopting a 10% difference as the threshold for acceptability, the measurement interval at this site should remain shorter than 4 h to support TSS_L (Fig. 6a) and T_{nL} (similar behavior to TSS_L) estimates for runoff events and not more than 12 h for longer-term (*e.g.*, month) estimates (Fig. 6b). Loading estimates were systematically lower for further increases in the sampling interval for the five month period (Fig. 6b). The effect was considered largely progressive; *e.g.*, the apparent improvement for an increase in the sampling interval from 1 to 2 d was a random chance occurrence (Fig. 6b). The percent differences exceeded 40% for sampling intervals ≥ 4 d. As a practical matter, there was essentially no cost for the high frequency T_n measurement regime adopted in this study.

Onondaga Creek represented ~60% of the total TSS_L from the three largest tributaries to the lake over the 2001-2005 (water years) period (Table 3). This corresponded to nearly twice the contribution of Ninemile Creek, which provided an equivalent hydrologic input (Effler 1996). The breakdown of contributions by these tributaries was subject to year-to-year variations, primarily because of the differences in TSS - Q relationships (Fig. 5e). Onondaga Creek became relatively more important in high runoff years. For example, this tributary was estimated to represent nearly 70% of the total TSS_L for water year 2004 (Table 3), which had the third highest flow for the 54-y record (for Dorwin Avenue). Other tributaries to the lake made both small hydrologic and TSS contributions (Effler 1996). The TSS of all the lake’s tributaries was dominated by inorganic constituents (Yin and Johnson 1984). Concentrations of TSS were lower in the effluent of the wastewater treatment facility and composed primarily of organic material (Yin and Johnson 1984, Effler 1996). Thus, Onondaga Creek was the dominant allochthonous source of inorganic particulate material to Onondaga Lake.

Table 3.— TSS - Q relationships for the three largest tributaries to Onondaga Lake for water years 2001-2005, with percent contributions to total tributary TSS_L .

Creek	Relationship	r^2	% Contribution to Total TSS_L^*	
			2001-2005 ⁺	2004 ⁺
Onondaga	$TSS = 6.66 \cdot Q^{0.69}$	0.399	59	68
Ninemile	$TSS = 6.03 \cdot Q^{0.45}$	0.206	33	28
Ley	$TSS = 12.04 \cdot Q^{0.30}$	0.166	8	4

* sum of TSS_L for the three tributaries

⁺ water years

Impacts on Onondaga Creek and the harbor

High concentrations of clay minerals can cause direct negative effects on biota, including mortality, reduced physiological function, and habitat alienation, as well as indirect effects linked to reduced food supply (Newcombe 2003). The sediment deposits in upstream deposition zones and high turbidity levels have greatly modified the benthic macroinvertebrate community of the stream. Diversity, richness and density have been reported (Effler 1996) to be substantially lower downstream of the mudboils compared to conditions at a reference site upstream of these inputs (Fig. 1). For example, a single sampling in June of 1991 showed that the population density at the upstream location was 2752 individuals/m², compared to only 139 individuals/m² at a downstream site (Effler 1996). Values of T_n frequently exceeded threshold levels during our study (Fig. 3b) corresponding to substantial impact for salmonids and other desirable game fish (Newcombe 2003). These degraded conditions are a particular concern for the Onondaga Nation that adjoins this portion of the stream impacted by the mudboils (Fig. 1). Anecdotal information from the Onondaga Nation and earlier European settlers indicates the stream had been rich in salmonids throughout its length before the 1900s (Effler 1996). Currently, salmonids are not found in the main stem of this stream from the area of the mudboils down to the mouth.

The harbor is severely impacted by the high sediment load with respect to deposition and esthetics. Dredging has been required on several occasions since the early 1900s to support navigation. Major increases in T_n and decreases in Secchi disc transparency (minima ~0.1 m), and a brown "muddy" appearance, are observed in the harbor from runoff events; features that persist several days thereafter (Effler *et al.* 1992). Turbidity values of ~100 NTU were reported for an event with Q_p ~10 m³/s in 1988, yet higher values probably occurred on a number of occasions during this study, as Q_p exceeded that value for 12 events (Fig. 3a). Degraded esthetics prevailed in the harbor for much of the study period in this high runoff year, conditions that are particularly undesirable within the context of ongoing redevelopment plans to locate entertainment venues at the site.

Impacts on Onondaga Lake

Management context

In the late 1980s Onondaga Lake was described as the nation's most polluted lake (Onondaga Lake Restoration Act of 1989, Hennigan 1990), associated with profound impacts from both industrial and domestic wastes (Effler 1996). Two rehabilitation programs are currently proceeding in parallel for the lake; one is directed at residual contaminants (particularly mercury) from industrial pollution (soda

ash/chlor-alkali manufacturing, cleanup ~\$450 million), the other addresses domestic waste (~\$400 million). The bottom of the lake is a Superfund site because of contamination with mercury and toxic organics from the industry. One of the five elements of the cleanup program for the Superfund site is burial of contaminated pelagic sediments through continued sedimentation, described as "monitored natural recovery" by the New York State Department of Environmental Conservation (NYSDEC 2005). Other elements of the cleanup include dredging and capping of the more highly contaminated near-shore sediments adjoining the industrial facility (NYSDEC 2005).

One important element of the domestic waste rehabilitation program is major reductions in phosphorus loading from a direct discharge by a wastewater treatment facility, with the goal of abating the manifestations of severe cultural eutrophication (Effler *et al.* 2002a). A primary benefit sought by the program is improved optical esthetics, particularly increased water clarity, associated with reductions in concentrations of phytoplankton biomass. However, the potential benefits of such programs need to be considered in the context of the effects of other light-attenuating constituents (Effler and Perkins 1996, Perkins and Effler 1996). In particular, high light scattering contributions from inorganic particles (tripton; Wetzel 2001) can mask the benefits of reductions in phytoplankton (Kirk 1985, Effler *et al.* 2000, 2002b).

As the dominant allochthonous source of sediment to the lake, the load from Onondaga Creek is a concern for both rehabilitation initiatives, within the context of burial of contaminants in the Superfund site and influencing clarity conditions in the lake. Interestingly, the Superfund site concerns are related to the mass deposition potential from this source, whereas the domestic waste initiative is sensitive to the optical (*e.g.*, turbidity, clarity) implications of this input. Moreover, the concerns for this source of sediment are incongruent for the two management initiatives; *e.g.*, more would be good for burial of contaminated sediment, but potentially bad for optical esthetics. The available information suggests this source of sediment is important for both initiatives.

Deposition/sedimentation

The recent sediments of the pelagic zone of the lake are dominated by inorganic constituents (~85% of dry weight; Effler 1996). This material has both allochthonous and autochthonous origins (Yin and Johnson 1984, Womble *et al.* 1996). Large quantities of calcium carbonate (CaCO₃) have precipitated and been deposited within the lake as a result of high Ca²⁺ concentrations that resulted from the industry's discharge (Womble *et al.* 1996). This autochthonous source of sediment (*i.e.*, burial) decreased substantially following cessation of manufacturing (and corresponding decreases in Ca²⁺ concentrations). Based on analyses of sediment trap

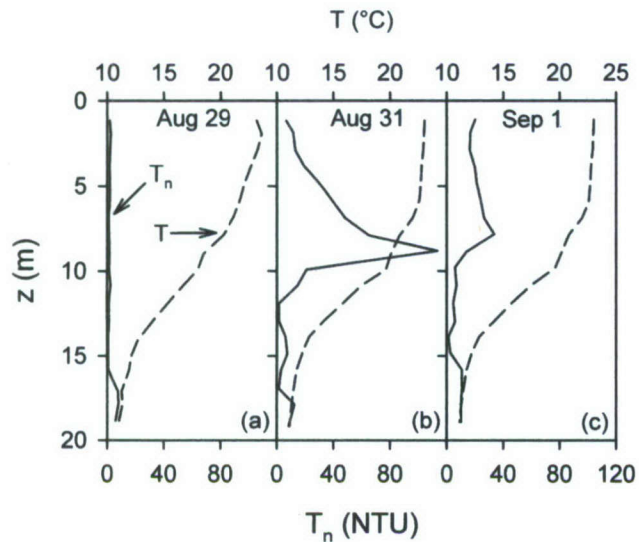


Figure 7.—Profiles of turbidity (T_n) and temperature (T) in Onondaga Lake for three days in 2004 that depict impact from Onondaga Creek associated with runoff event No. 36: (a) August 29, (b) August 31, and (c) September 1 (modified from Effler *et al.* 2006a).

collections, Womble *et al.* (1996) estimated the annual deposition of CaCO_3 , under prevailing Ca^{2+} concentrations, to be ~24,000 mt. Further reductions can reasonably be anticipated as residual Ca^{2+} waste inputs are remediated and primary production decreases (Hodell *et al.* 1998).

The estimated allochthonous load from Onondaga Creek for the study year (~30,000 mt) was 25% higher than the estimated autochthonously produced CaCO_3 deposition. However, this comparison is imperfect for at least two reasons. First, it does not accommodate the effects of year-to-year differences in this stream's load associated with interannual variations in runoff. Second, it does not take into account systematic reductions in effective loading to the pelagic zone that occur due to localized deposition adjoining the stream inflow. The TSS-Q relationship (Fig. 5b), in combination with the long-term (54 y) flow record for the monitoring site, represents a basis to support a first approximation of the magnitude of average sediment loading and interannual differences for Onondaga Creek. There is substantial uncertainty in whether the prevailing TSS-Q relationship is representative of the period of flow measurement; *e.g.*, the history of sediment loading to the stream from the mudboils is poorly defined, though such structures were known in the area before gauging commenced (Kappel and McPherson 1998). However, such estimates are probably reasonable representations for future variability, because the pool of resuspendable sediment (stream bed and bank deposits) above the monitoring site apparently is large (Effler *et al.* 1992). The lack of shifts to decreased TSS load of Onondaga Creek in response to the

reductions in external loading from the mud boils (Kappel and McPherson 1998) further supports that position. Accordingly, the average annual load would be ~19,500 mt (~20% less than the estimated deposition of CaCO_3), but with wide interannual variations, ranging from 3,581 to 49,961 mt (coefficient of variation = 0.502).

Localized deposition diminishes the TSS_L carried to the stream mouth before it reaches the pelagic zone of the lake, though the effect remains poorly quantified. In addition to the losses that occur within the harbor (*e.g.*, dredging requirement), localized depositional losses apparently also occur in the near-shore zone bounding the entry from the harbor into the lake. In a surficial sediment survey of the entire lake, Auer *et al.* (1996) observed particularly high clastics content (*e.g.*, clay minerals; Rowell 1996) adjoining the entry of Onondaga Creek. Despite these localized losses, the paleolimnological record suggests clay minerals (*i.e.*, the Onondaga Creek TSS_L) are an important component of the pelagic sediments; Rowell (1996) reported clastics were ~40% of dry weight solids in the upper sediments for a core sample collected in the middle of the lake's southern basin (Fig. 1).

Turbidity/clarity

The effects of turbidity inputs from Onondaga Creek on the optical water quality of the lake can be partitioned between runoff events and longer intervals (*e.g.*, seasonal). The delivery of large quantities of sediment from this tributary during runoff events caused conspicuous short-term increases in T_n in the lake (Effler *et al.* 2006a). Resolution of this impact has been supported by the operation of a robotic profiling platform in the lake's southern basin since 2000 (1-m profiles, at least daily, April-October; Effler *et al.* 2006a), equipped with various sensors that include measurement of T_n (YSI model No. 6136, see Table 1). Major increases in T_n were observed at this lake site about a day after Qp for events 33, 36, 37 and 38 (Effler *et al.* 2006a). In each of these cases the maximum impact occurred in subsurface layers (*e.g.*, Fig. 7), indicating the entry of Onondaga Creek as a plunging inflow (density current). However, impact on surface water optical conditions was also observed for such events (Fig. 7b), and surface T_n levels subsequently increased further in response to mixing effects within the lake (Fig. 7c). A wide range of vertical distributions of the stream's turbidity in the lake's water column has been documented following runoff events (Effler *et al.* 2006a, including as a buoyant overflow) that reflects seasonal variations in the buoyancy of the Onondaga Creek inflow (Effler *et al.* 2002a).

Onondaga Lake is an optically complex system because strong uncoupled variations in several light attenuating constituents and common metrics of optical water quality occur (Effler and Perkins 1996). Analyses conducted with a calibrated mechanistic optics model demonstrated non-

CaCO_3 inorganic tripton (*e.g.*, clay minerals) was the second most important regulator of Secchi disc transparency (SD) in the lake (after phytoplankton) for the spring to fall interval in 1988. Inflow from Onondaga Creek over this interval in 1988 ranked 48th out of the 54-y record, suggesting particle inputs from this source are important in many years. Thus, this allochthonous source of sediment limits the improvement that can be anticipated for clarity in response to nutrient control strategies, even during dry weather intervals (Effler and Perkins 1996).

The ALI image of September 29, 2002, clearly depicted a turbid plume in Onondaga Lake emanating from the mouth of Onondaga Creek (Fig. 8a). The derived contours of c_{550} depicted strong spatial variations in the lake's upper waters, with localized high c_{550} (*i.e.*, T_n) levels along the lake's eastern shore within the plume (Fig. 8b). The peak c_{550} value in this region was estimated to be $\sim 4 \text{ m}^{-1}$ (*i.e.*, $T_n \sim 9 \text{ NTU}$), compared to $\sim 1.8 \text{ m}^{-1}$ at mid-basin locations (Fig. 8b). The mid-basin value is generally consistent with T_n observations for that day made at the site of the robotic monitoring platform (unpublished data, Upstate Freshwater Institute). This image corresponded to a minor runoff event (increase in Q from 0.6 to $2.7 \text{ m}^3/\text{s}$ on September 28; *e.g.*, Fig. 3a), suggesting the occurrences of such turbidity plumes from this stream's input are probably common. Other satellite images (*e.g.*, Effler 1996) have also depicted plumes emanating from Onondaga Creek. These patterns cause spatially heterogeneous optical characteristics that doubtless vary in response to ambient lake mixing (*i.e.*, meteorological) conditions, and may result in spatial variations in deposition and net sedimentation within the pelagic zone.

The need for a quantitative management tool

Given the indicated importance of inorganic particle loading from Onondaga Creek for sedimentation, turbidity and clarity (*i.e.*, water clarity; Effler 1988) in Onondaga Lake, and the increased relative importance that is expected with the progression of the underway rehabilitation programs, an appropriate model(s) is recommended to quantify these impacts and establish reasonable expectations for these basic limnological attributes. Managers and stakeholders will be concerned with the magnitudes and spatial patterns of impact on water clarity and burial of contaminants in the sediments. Model development and testing would require the support of a data collection program to quantify the driving conditions of this tributary's sediment load and autochthonous production of CaCO_3 , as well as model state variable patterns within the lake. The automated monitoring unit used in this study would play a key role by quantifying the dynamics of the dominant source of allochthonous inorganic particles (*e.g.*, Fig. 3c and d). Features of the findings and analysis presented here serve to guide model design.



Figure 8.—(a). Image from Advanced Landsat Imager (ALI) for September 29, 2002 depicting turbid plume along the eastern shore of Onondaga Lake from the Onondaga Creek input, and (b) corresponding derived contours of the beam attenuation coefficient (c_{550}).

The model state variables would, as a minimum, include both T_n and TSS because of fundamental differences in the size dependencies of light scattering and mass attributes of inorganic particles. For example, loss rates for T_n supplied from Onondaga Creek could reasonably be expected to be lower than for TSS because of the lower dependence of light scattering on the larger (*i.e.*, more rapidly settling) particles (Davies-Colley *et al.* 1993, Kirk 1994). Model simulations of T_n and TSS would in turn support predictions of water clarity (Effler and Perkins 1996) and net sedimentation (Effler 1996). A more robust and mechanistically attractive approach would be to adopt, as state variables, multiple particle size classes that represent the population of particles that regulate both

T_n and TSS. Simulated concentrations of the size classes would then be converted to TSS and T_n . This approach would dictate the inclusion of particle sizing and counting (Agrawal and Pottsmith 2000) and chemical characterization (Peng *et al.* 2004) technologies to characterize the populations with respect to mass (size and density) and light scattering (size and refractive indices; *e.g.*, Mie Theory; Kirk 1994) behavior in both Onondaga Creek and the lake. The spatially heterogeneous patterns for T_n imparted to the lake (Figs. 7 and 8) from this source indicates the need for water column monitoring, and probably modeling (Martin and McCutcheon 1999), in three dimensions, and measurements of deposition (sediment traps) and net sedimentation (core analyses) in two dimensions (longitudinal and lateral). A three-dimensional dynamic model could support simulations over time (events to seasonal) and depict vertical (*e.g.*, Fig. 7), lateral and longitudinal (*e.g.*, Fig. 8) patterns. Such a model could also have broader utility for ultimately supporting the development of a predictive tool for the transport and fate of contaminants that partition onto particles (Chapra 1997).

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14. ABSTRACT The implementation of an automated stream monitoring unit that features four probe-based turbidity (Tn) measurements per hour and the capability to collect frequent (e.g., hourly) samples for total suspended solids (TSS) analyses during runoff events to assess the dynamics of Tn, TSS and corresponding loads in sediment-rich Onondaga Creek, NY, was documented. Major increases in both Tn (maximum of 3,500 NTU) and TSS (maximum of 1630 mg/L) were reported for the stream during runoff events. Relationships between Tn, TSS and stream flow (Q) were developed and applied to support estimates of TSS loading (TSSL). Tn was demonstrated to be a better predictor of TSS than Q, supporting the use of the frequent field Tn measurements to estimate TSSL. During the year of intensive monitoring, 65% of the TSSL was delivered during the six largest runoff events that represented 18% of the annual flow. The high Tn levels and extensive in-stream deposition have negatively impacted the stream's biota and the esthetics of a downstream harbor. Onondaga Creek is reported to be the dominant allochthonous source of inorganic particulate material to downstream Onondaga Lake. These sediment inputs have important implications for the lake, within the context of two on-going rehabilitation programs aimed at contaminated lake sediments and the effects of extreme cultural eutrophication, by contributing substantially to sedimentation and turbidity. A satellite image documented the occurrence of a conspicuous turbidity plume that emanated from Onondaga Creek following a minor runoff event, suggesting such an effect is common and that related impacts are not spatially uniform.					
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